Solar Energy Forecasting Using Numerical Weather Prediction (NWP) Models

Patrick Mathiesen, Sanyo Fellow, UCSD

Jan Kleissl, UCSD

Solar Radiation Reaching the Surface

Incoming solar radiation can be reflected, absorbed, or transmitted to the surface

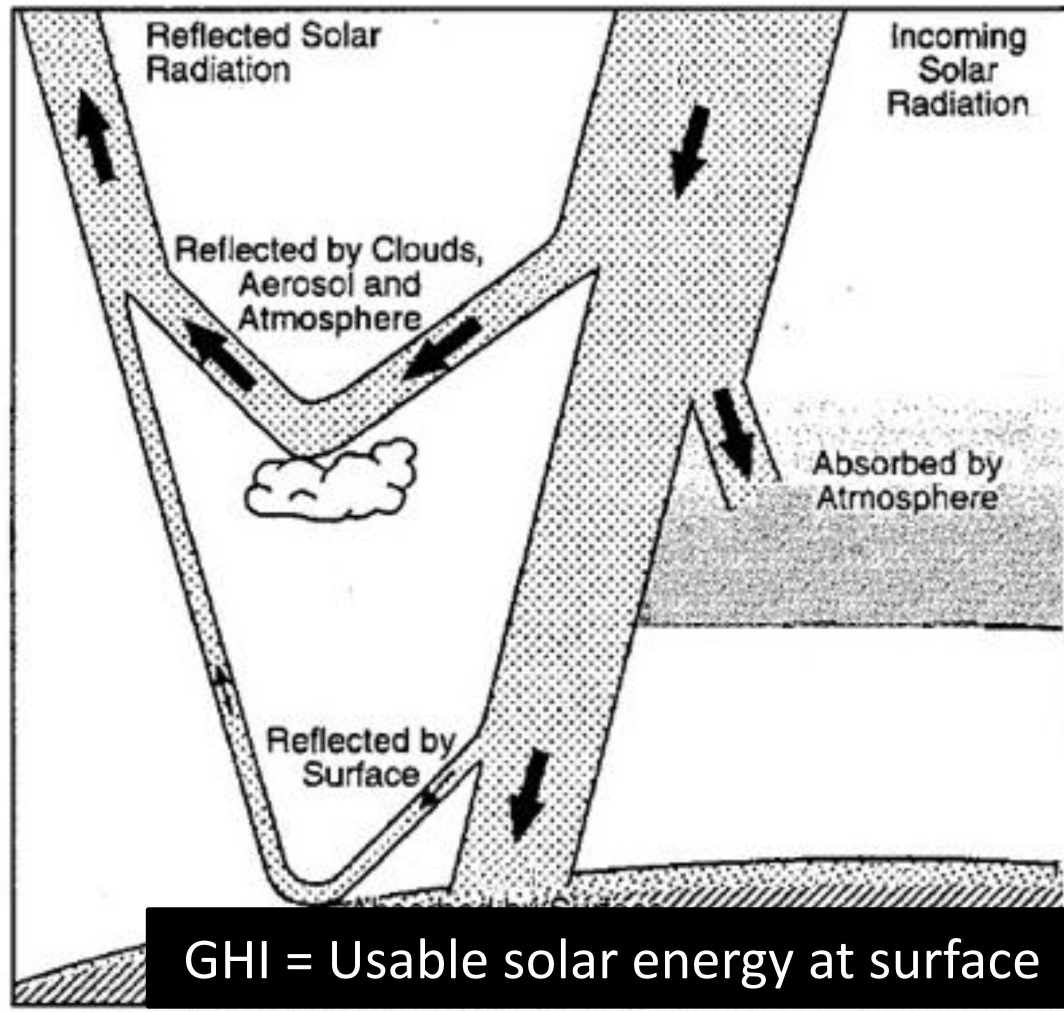
Difficulty of Predicting

Incoming Solar Radiation
- Date/Time

Geometry Effects
- Location
- Date/Time
  - Incoming Angle

Atmospheric Effects
- Trace gases
- Aerosols
- Water vapor

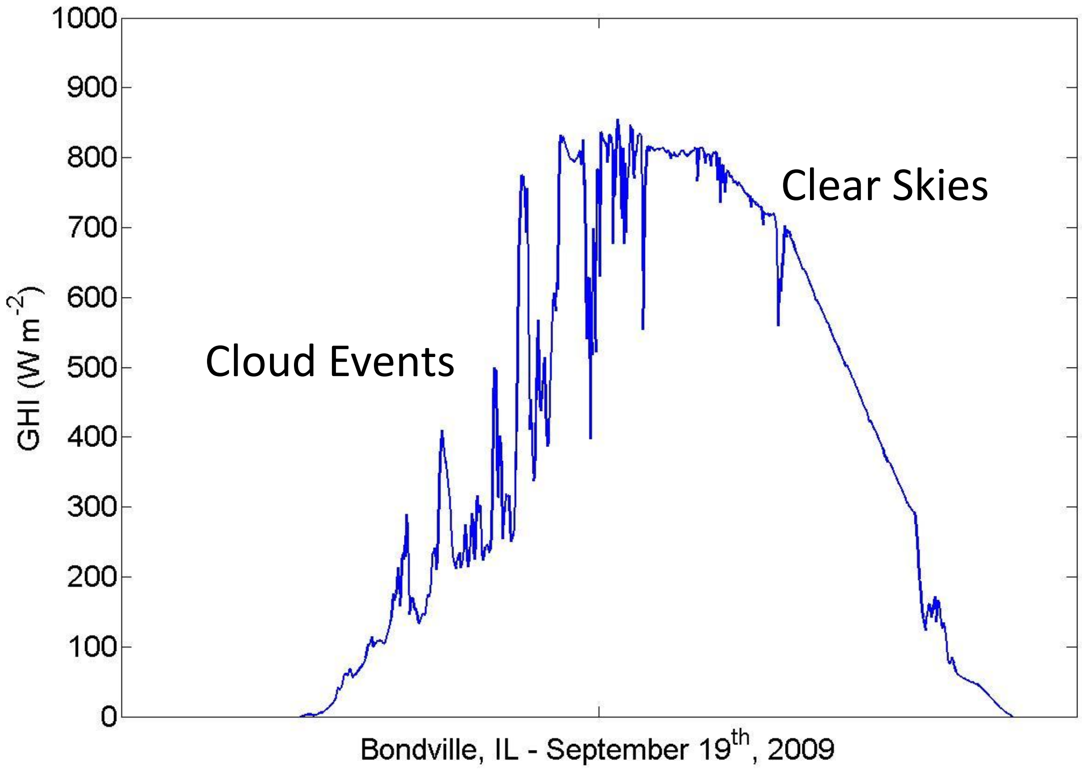
Cloud Effects
- Liquid water content
- Composition



Kiehl and Trenberth, 1997

Surface GHI is Highly Variable

Large variability in surface GHI is undesirable for utility scale applications



Atmospheric Conditions

- Static intra-hour conditions
- Effect on surface GHI is consistent and well documented

Cloud Conditions

- Dynamic weather conditions change on short time scales
- Difficult to predict
- Clouds are the largest contributors to GHI variability

Solar Forecasting Methods are Designed to Predict Cloud Dynamics

Solar forecasting mitigates high GHI variability – increasing efficiency of PV plants

Clear Sky Models

- Function of date, time, and location only
- Accurate for sunny conditions

Persistence Modeling

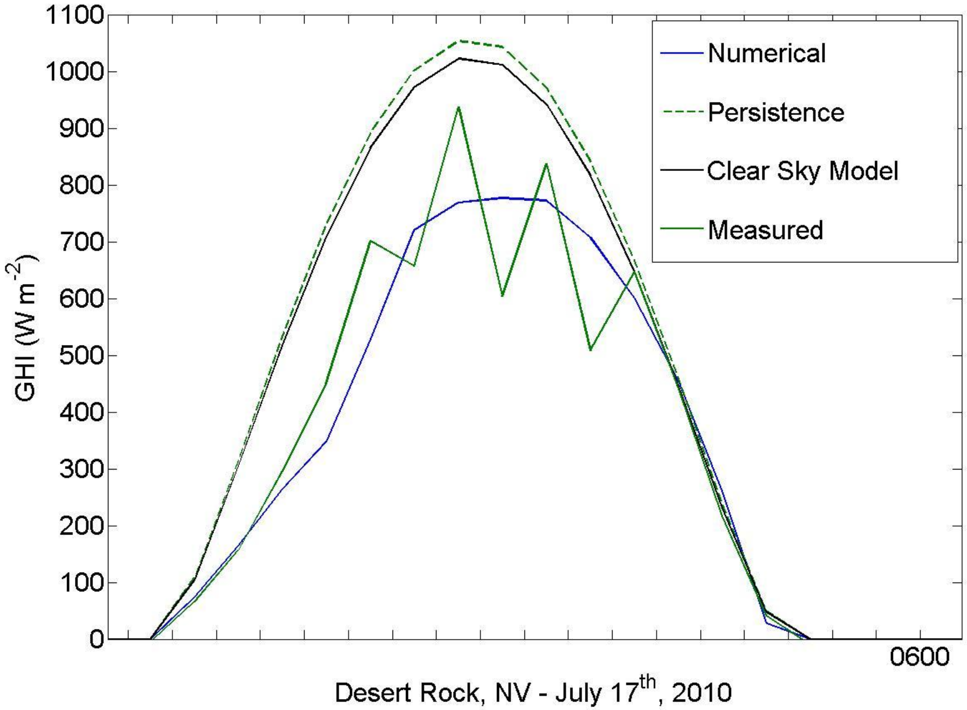
- Assumes conditions remain static for hours or more

Cloud Detection and Forecasting

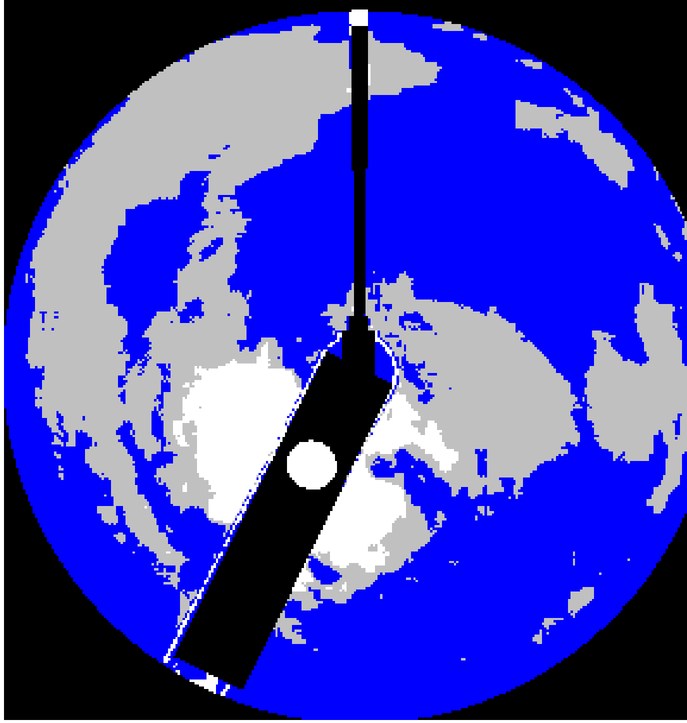
- Local sky imagery (minutes ahead)
- Satellite imagery (hours ahead)

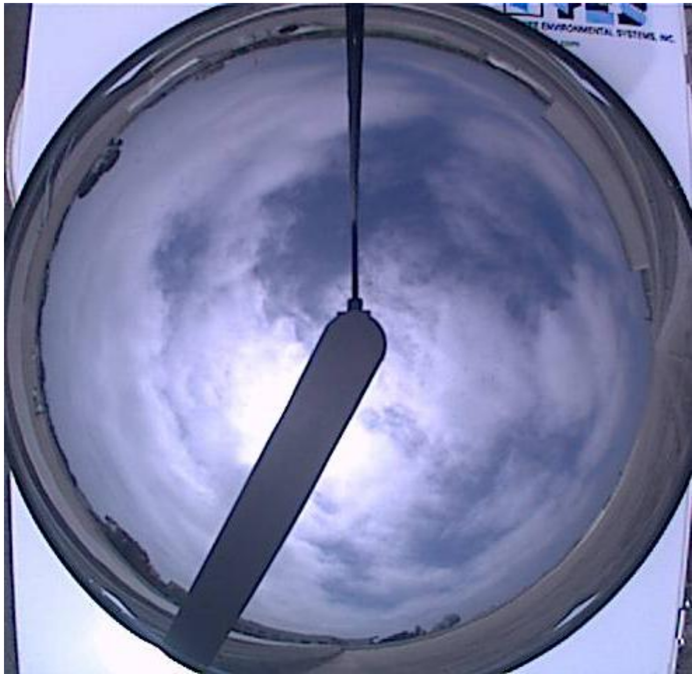
Numerical Weather Prediction

- Intra-hour to days ahead prediction of large scale weather patterns



Local Sky Imagery: Cloud Motion Detection

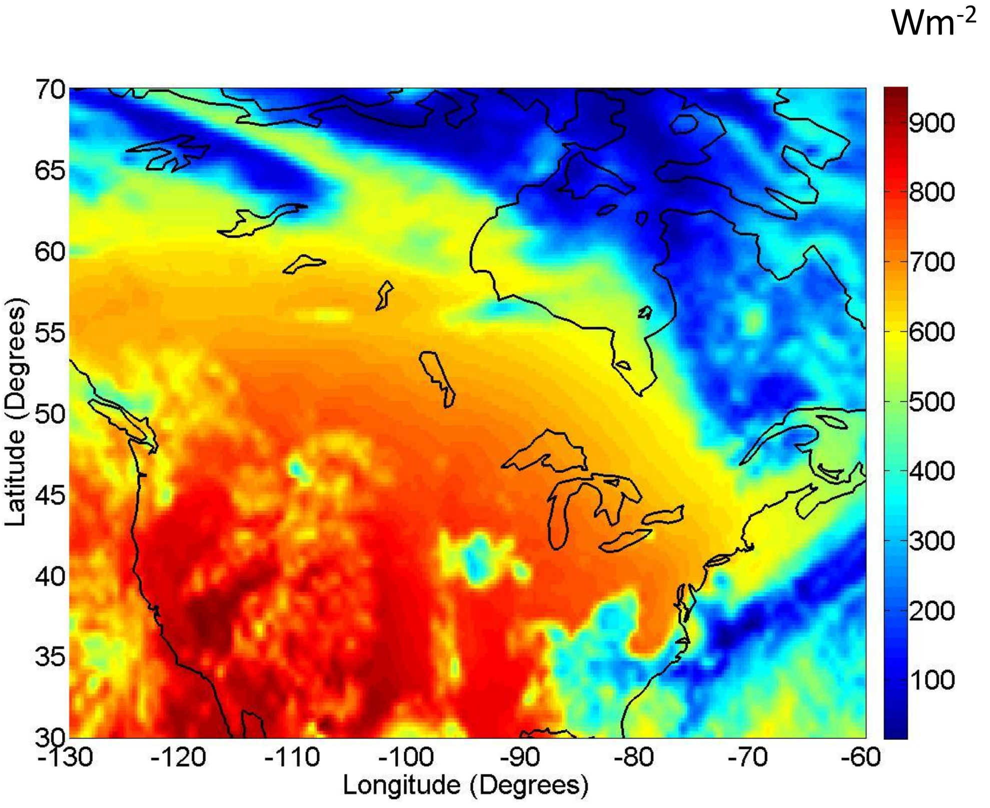




Numerical Solar Forecasting

Numerical Weather Prediction (NWP) simulations predict weather patterns essential for determining surface radiation

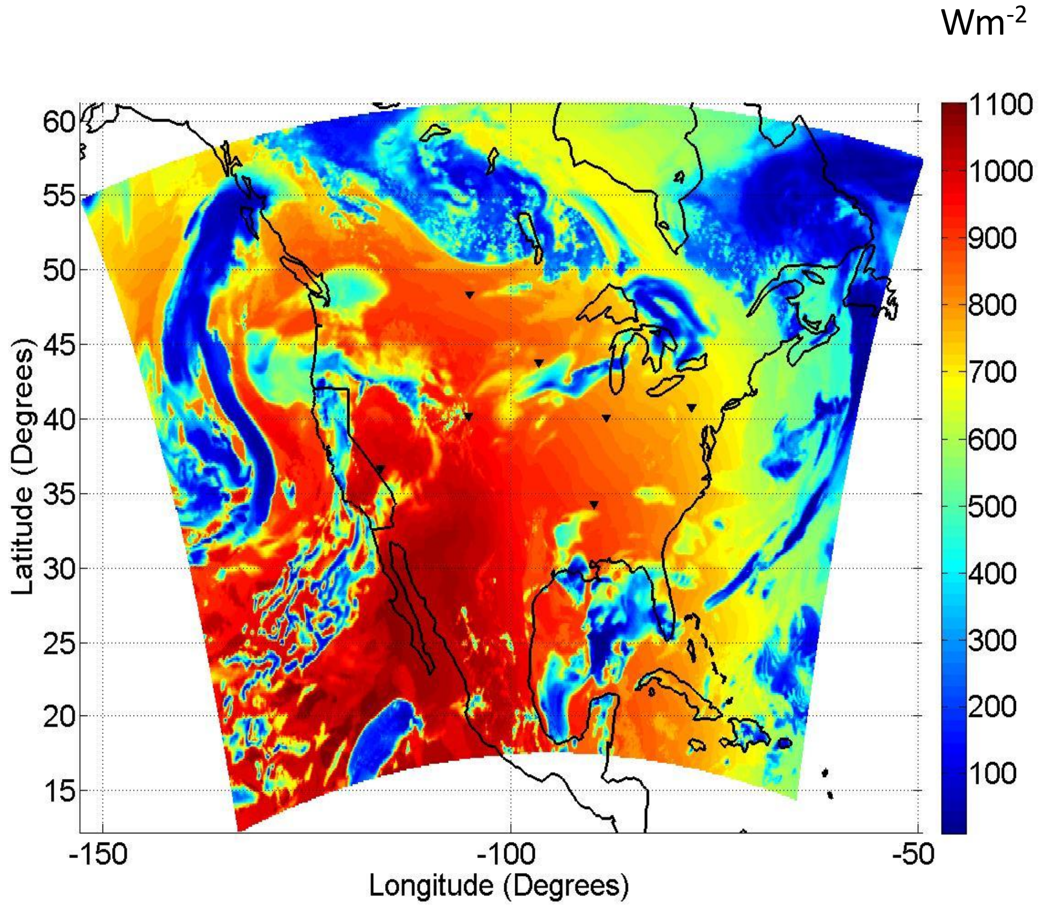
- Conservation of mass, energy, and water equations numericall solved
  - Prognostic Variables: Temp, pressure, water mixing ratio, etc.
- Radiative models calculate surface GHI
  - Parameters: Water Vapor, ozone, trace gases, aerosols, cloud parameterizations
- Models Analyzed: North American Mesoscale Model (NAM), Global Forecasting System (GFS), and European Centre for Medium Range Weather Forecasts (ECMWF)
  - NAM/GFS are freely distributed weather forecasts



NWP GHI Outputs are Biased!

GHI forecasts using NWP are expected to be significantly biased

- NWP models are not designed for accurate solar radiation forecasting
  - Radiation used only to drive surface energy balance
  - Temporal variability unimportant
- Spatial discretizations are too coarse to resolve intermittent cloud dynamics
  - Only general cloud properties can be parameterized



Using MOS to Correct NWP Bias

NWP biases are consistent and predictable

Error Processing

- Compare to ground truth data
  - SURFRAD network
- Calculate mean bias error (MBE)
- Establish MBE as a function of forecast parameters
  - MBE profile may reveal information about under which conditions is the NWP scheme biased

$$BIAS = GHI_{FORECAST} - Observed$$

$$BIAS_{HISTORICAL} = F(parameters)$$

$$BIAS_{EXPECTED} = G(parameters)$$

Model Output Statistics (MOS) Correction

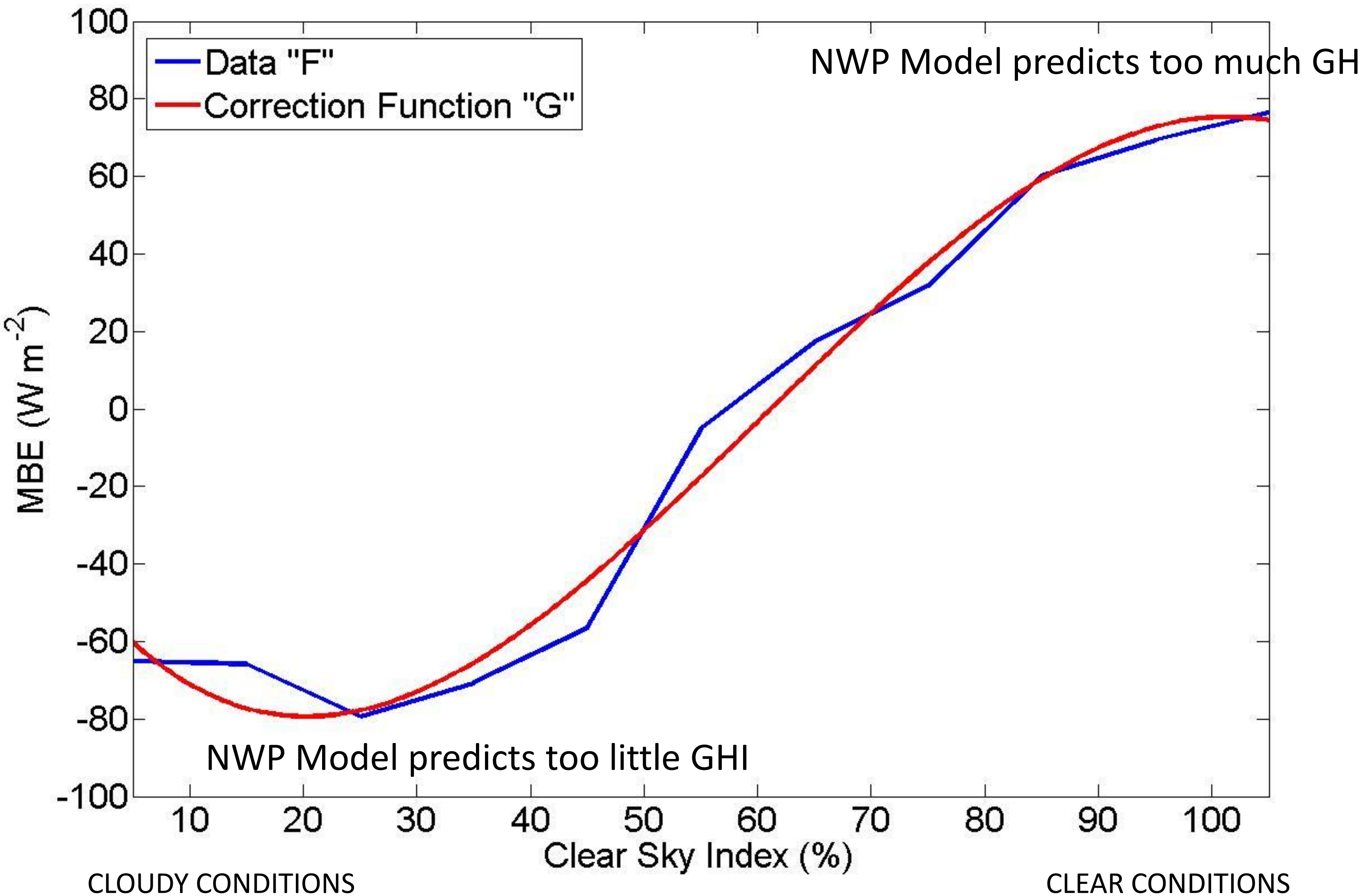
- Establish a correction function for MBE in terms of prognostic forecast variables
  - Prescribed an expected MBE for future forecasts
  - **Subtract expected bias from base forecast**

$$GHI_{IMPROVED} = GHI_{FORECAST} - BIAS_{EXPECTED}$$

More on the method: Lorenz et. al., 2009

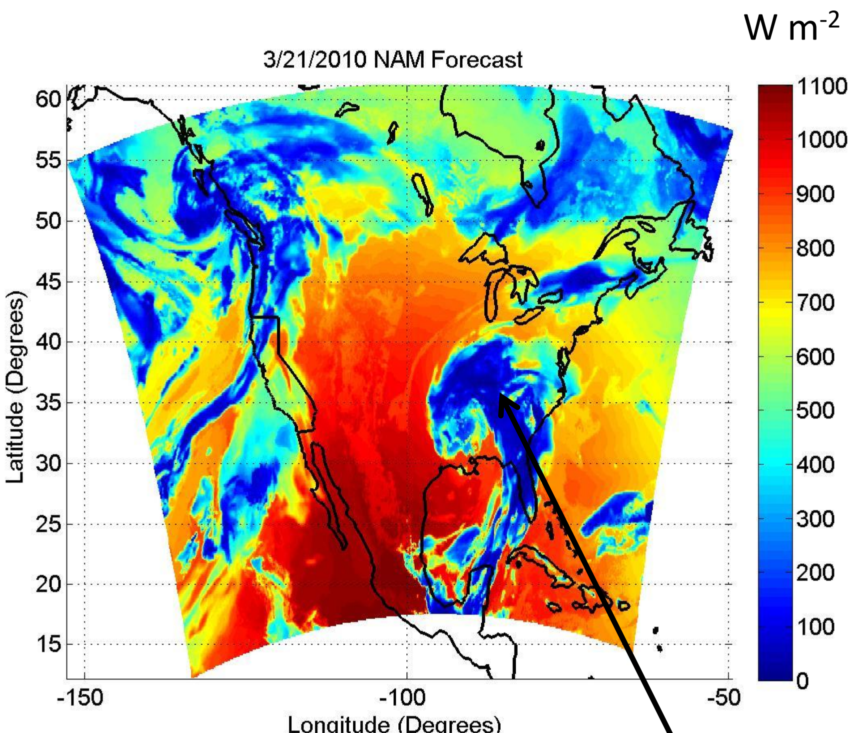
Example: Bias as a function of clear sky index

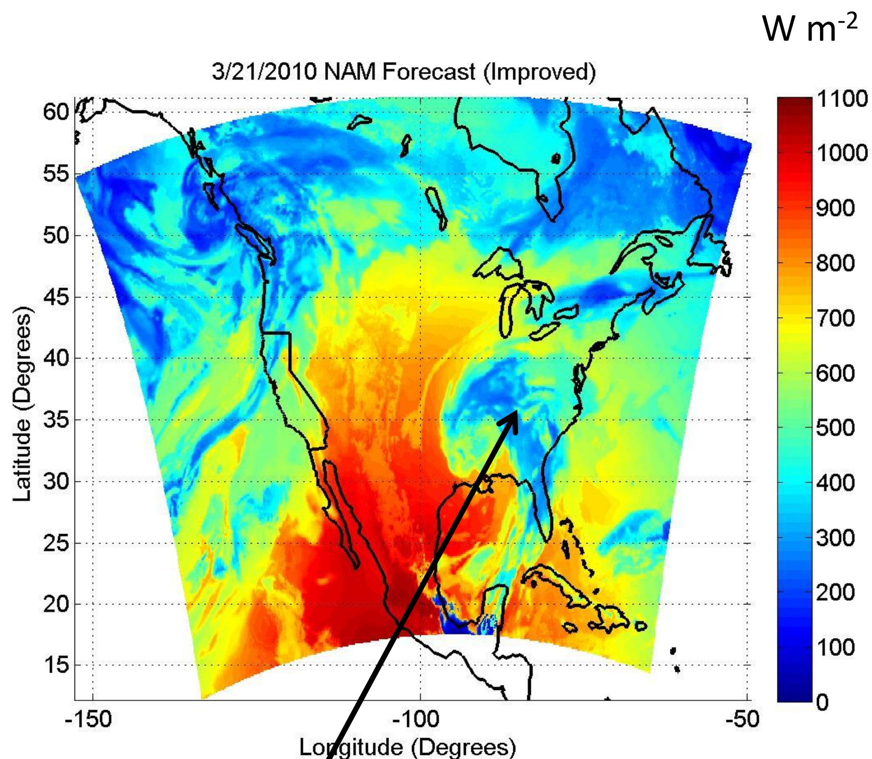
NWP model positively biased for clear skies and negatively biased for cloudy conditions



Bias Correction for a Single Forecast ($W\ m^{-2}$)

Based on clearness index, the basis NWP forecast can be improved





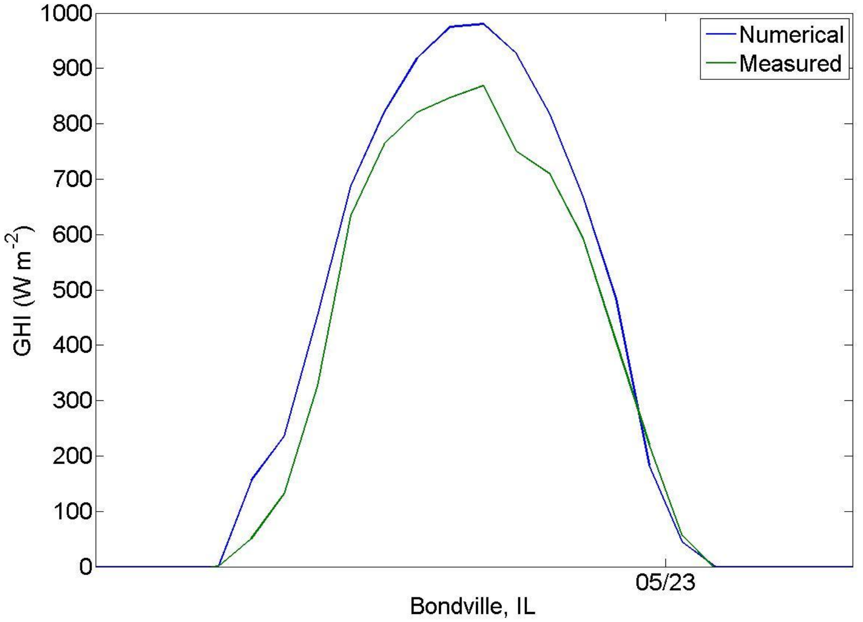
$$200\ Wm^{-2} - -80\ Wm^{-2} = GHI_{IMPROVED}$$

ORIGINAL FORECAST   EXPECTED BIAS

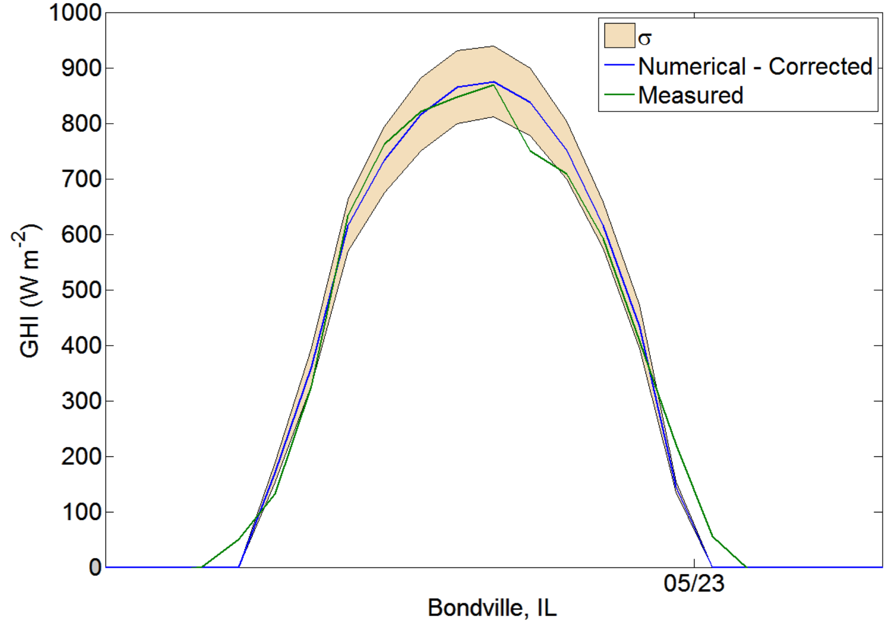
Prediction interval application

MOS correction improves forecast

Base Forecast



Corrected Forecast



MOS CORRECTION

Conclusions

NWP Models as a GHI Forecast

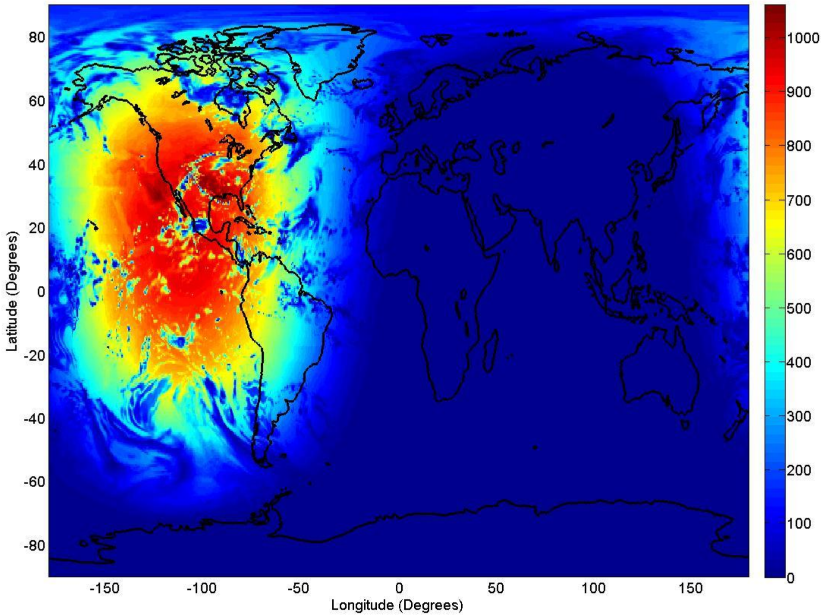
- Inherently biased
- Cloud parameterization is a likely source of error

Simple MOS Correction

- MOS correction reduces average MBE by nearly 40 W m^{-2} for most conditions

Next Steps

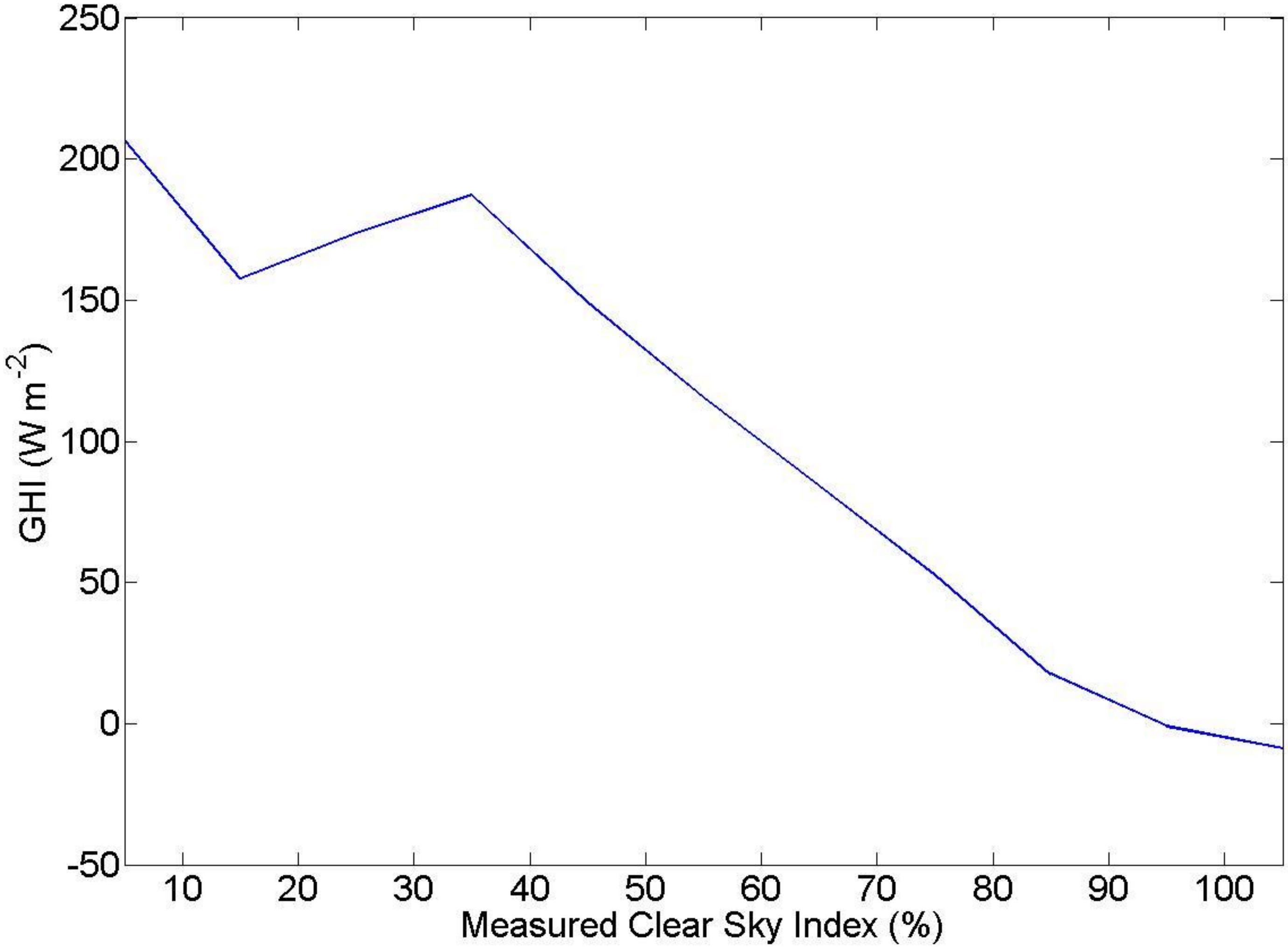
- Application of MOS to prognostic variables (such as liquid water content) to evaluate accuracy of cloud parameterization models



THANK YOU!

Acknowledgements: Sanyo Corporation

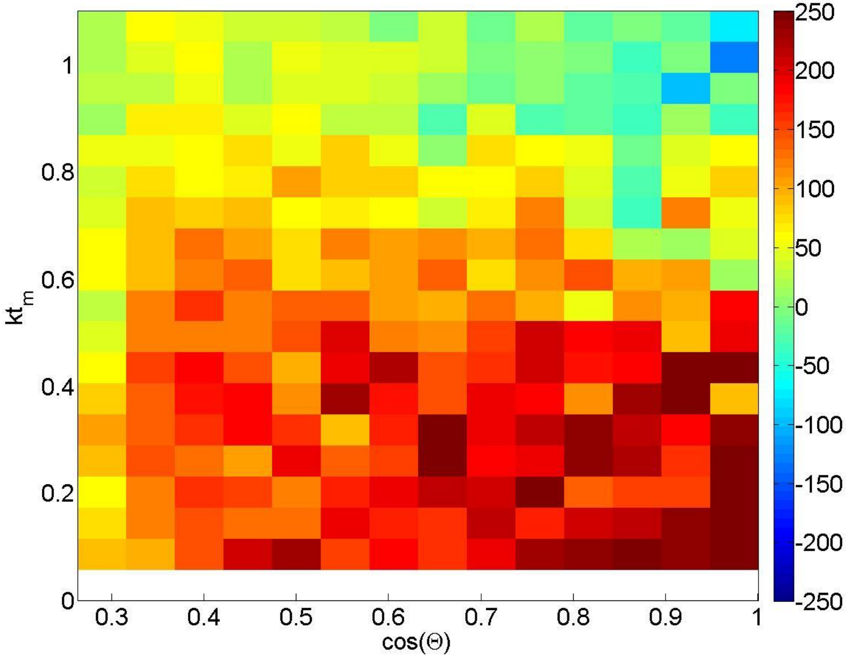
Where is the source of this error?



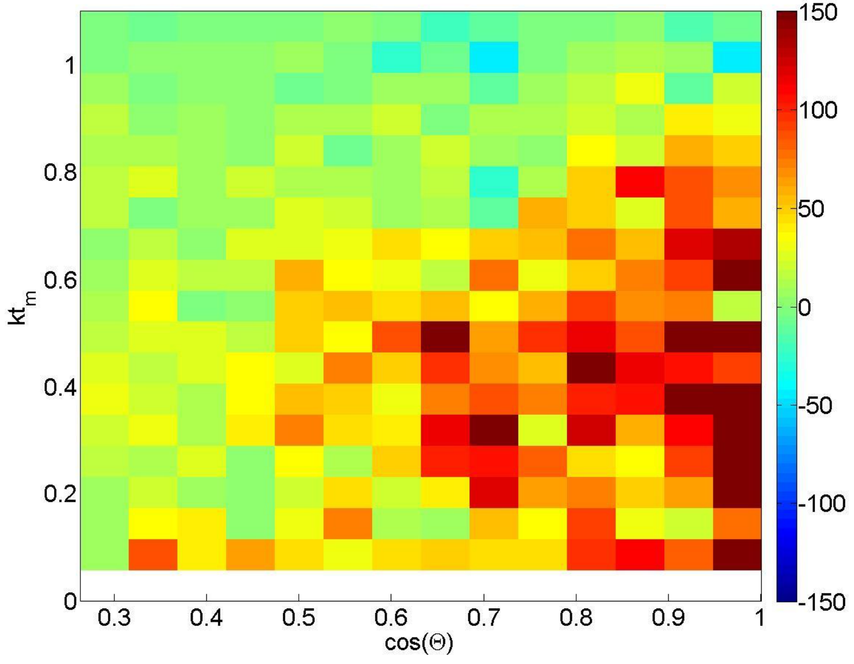
MBE as a Function of Measured Clear Sky Index (kt_m)

For true clear conditions ($kt_m > .9$) the radiative model is unbiased

NAM



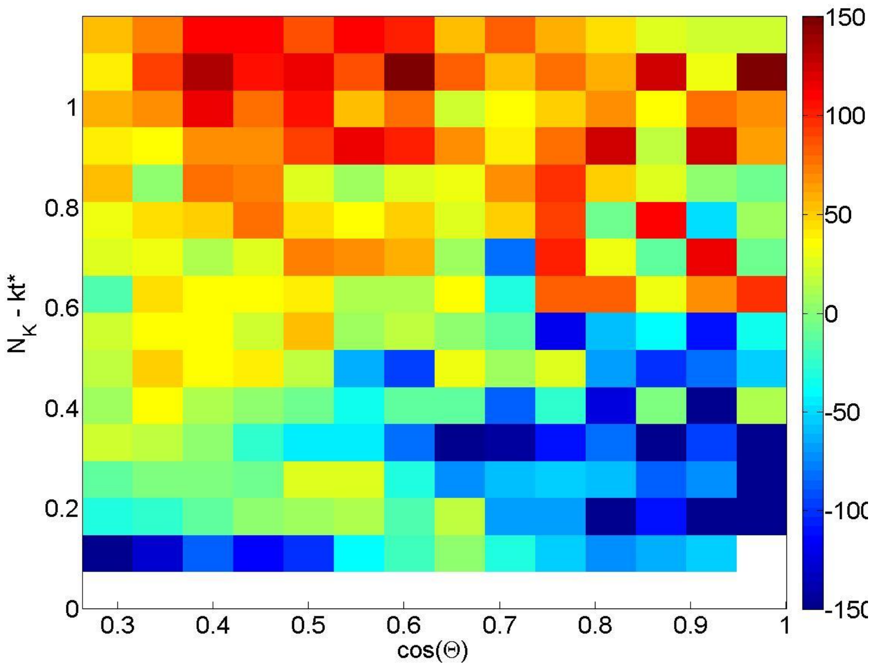
GFS



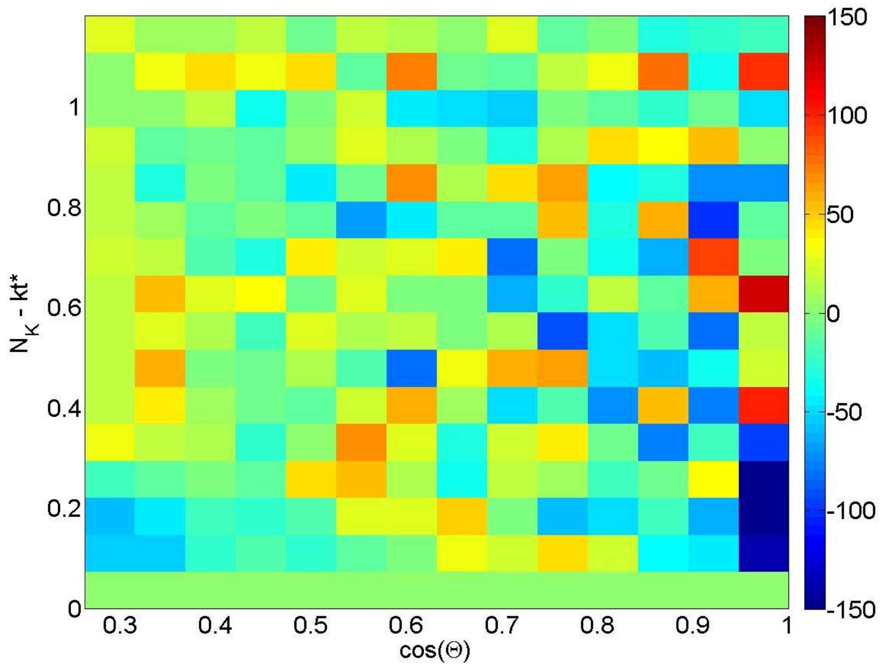
Two-Dimensional MOS (Wm^{-2})

MBE significantly reduced (~100 $W\ m^{-2}$) in target areas

Average MBE = 41.9 Wm^{-2}

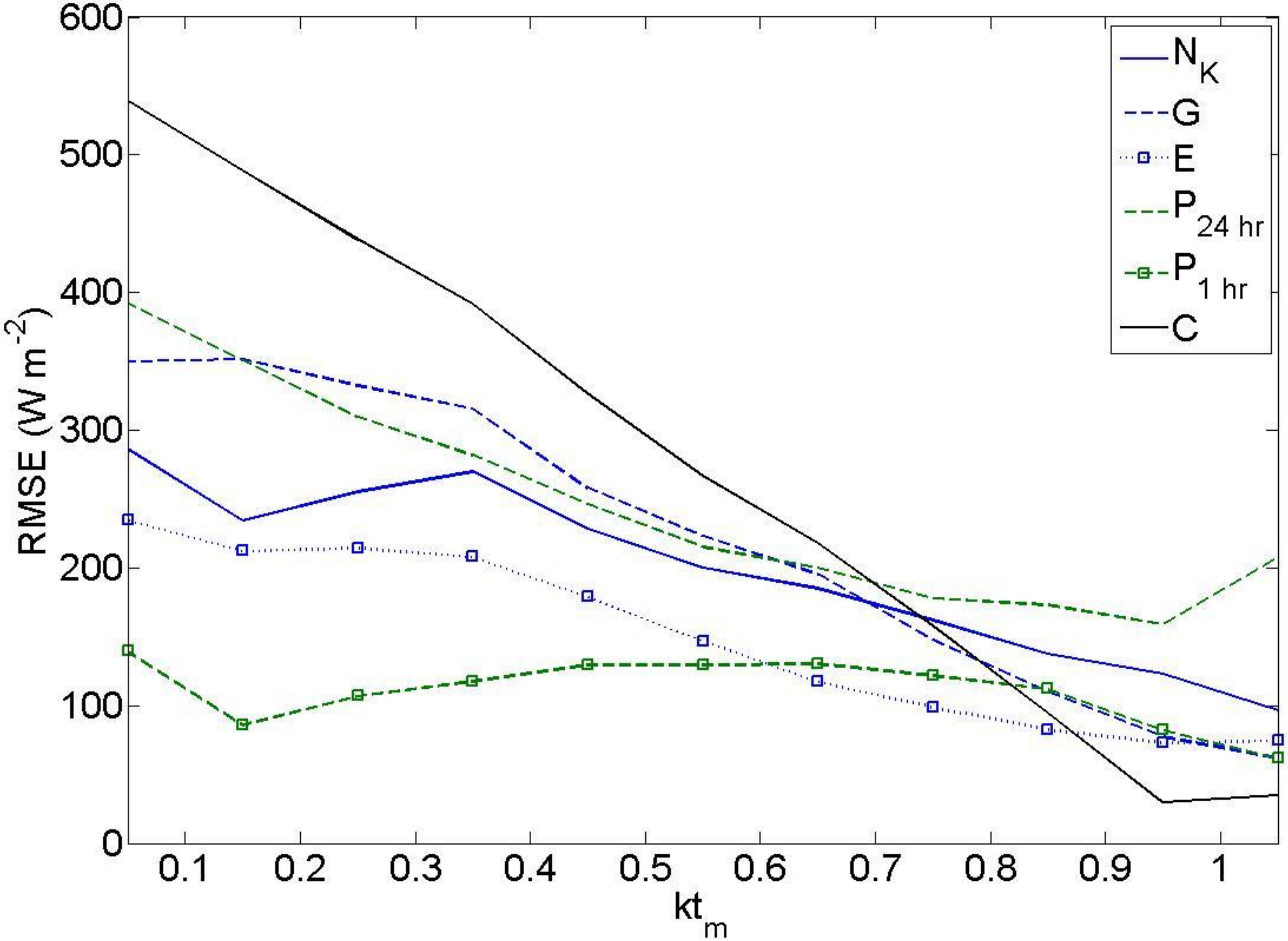


Average MBE = -2.9 Wm^{-2}



RMSE (Wm^{-2}) varies with measured clear sky index (kt_m)

In general, the ECMWF provides the best forecast



RMSE Improved Forecasts